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MOLECULAR CLOUDS IN THE GALAXY*

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ABSTRACT

The $J = 1 \rightarrow 0$ emission of CO has been surveyed in the galactic plane between $l = -10°$ and $+90°$ with a 1′ beam sampling every degree. Molecular clouds emitting in the CO line are plentiful over the inner region of the Galaxy. Their greatest number occurs in the galactic nucleus and at a radius of 5.5 kpc—a distribution similar to radio H II regions and galactic γ-ray emission but very different from that previously derived for atomic hydrogen. The total mass in molecular clouds is found to be 1–3 $\times 10^9$ $M_\odot$, and each typically has 10^5 $M_\odot$, an H_2 density of 700 cm^{-3}, and a temperature near 7 K. These results suggest that most of the interstellar medium in the interior of the Galaxy is molecular H_2.

Subject headings: galactic structure — Galaxy, The — molecules, interstellar

I. INTRODUCTION

Prerequisite for understanding galactic evolution is a knowledge of the large-scale distribution and total mass of dense interstellar clouds. Within these, the birth of stellar associations and clusters is currently taking place on a time scale short compared with the age of the Galaxy from a mixture of processed and primeval gas. These clouds are the active regions of the Milky Way. They are grossly underplayed in measurements of the 21-cm atomic hydrogen (H I) emission since most of the gas there will be molecular (H_2), and what little H I remains will generally be cool. Since the dense massive clouds that are the source of molecular radio emission lines have well over 5 mag of visual extinction, they are totally opaque in the ultraviolet; our knowledge of these regions must be derived from radiofrequency transitions of rarer molecules.

Clearly favored for a galactic survey of molecular regions is the $J = 1 \rightarrow 0$ emission of CO at 2.6 mm. In every extended source of radiofrequency molecular transitions the CO line is most intense; often it is found to maintain a high intensity even to the edge of molecular clouds where the density falls below 10^3 cm^{-3} (Penzias, Jefferts, and Wilson 1971; Liszt 1973).

The emission is optically thick in all dark clouds and is often thermalized in the line center. Since emission in the rotational line ultimately results from collisions of H_2 and CO, CO observations yield information on the H_2 density $n(H_2)$ and temperature T_k throughout the Galaxy.

We report here a preliminary survey of CO emission from the galactic plane. CO spectra were taken along the galactic equator over the longitude range $348° \leq l \leq 90°$. We randomly sampled the gas clouds throughout the Galaxy, avoiding the selection bias of most previous molecular observations toward compact H II regions or nearby dark clouds which appear on photographs. The observations were separated by 1° in longitude; selected longitudes ($l = 20°$, 30°, 41°, and 44°) were also mapped perpendicular to the galactic plane from $b = -1°$ to $+1°$ with a spacing Δb of 0°.25. The velocity coverage was varied with longitude so as to contain most of the gas indicated by H I surveys (Kerr 1969) and expected from galactic rotation. The CO data for $|l| \leq 3°$ were taken from our more detailed study of the galactic nucleus (Scoville, Solomon, and Jefferts 1974). The new observations for the remainder of the galactic plane were obtained in 1973 October with the 36-foot (11 m) antenna (HPBW = 1′.2) and receiver of the NRAO,[1] covering 166 km s^{-1} with a resolution of 0.65 km s^{-1}. The chopper wheel was employed for gain calibration, and all antenna temperatures were corrected for atmospheric attenuation (Davis and Vanden Bout 1973). The instrumental baseline was partially removed by switching 3° away from the plane, the maximum with the NRAO program.

II. DISTRIBUTION OF CO EMISSION

The emission lines are distributed nonuniformly in the spiral arms and galactic disk. The molecules in the galactic nucleus, between the nucleus and the solar circle, and those exterior to the Sun are easily distinguished in the longitude-velocity diagram, Figure 1.

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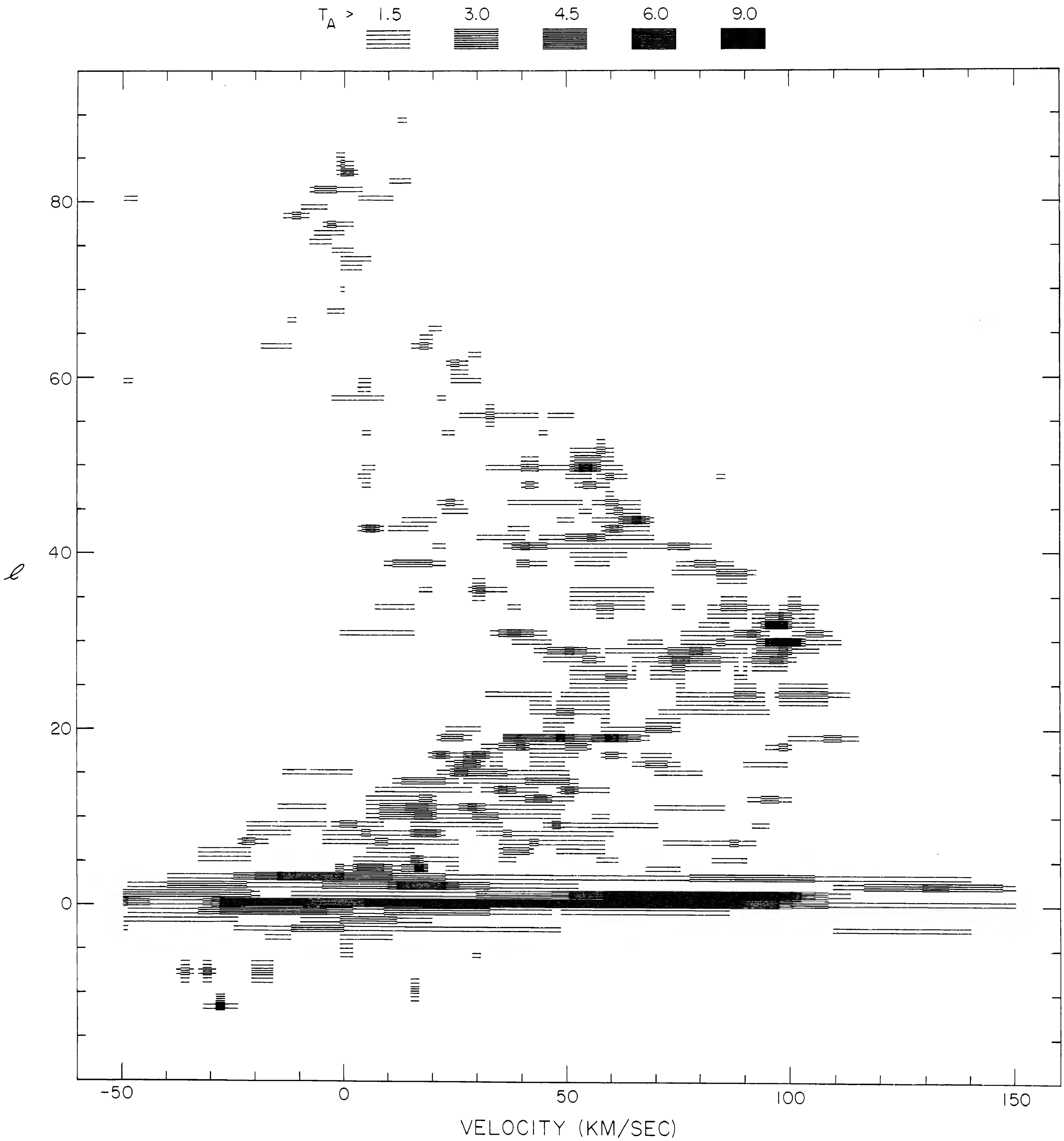

FIG. 1.—The intensity of CO emission along the galactic equator is shown as a function of longitude and velocity. Molecular emission tends toward lower longitudes and more positive radial velocities as compared with 21-cm (see Kerr 1969), indicating that the molecules are concentrated toward the center of the Galaxy. A version of this figure spanning more velocities (± 300 km s^{-1}), and therefore containing the full range found in the galactic center, may be found in Scoville (1975).

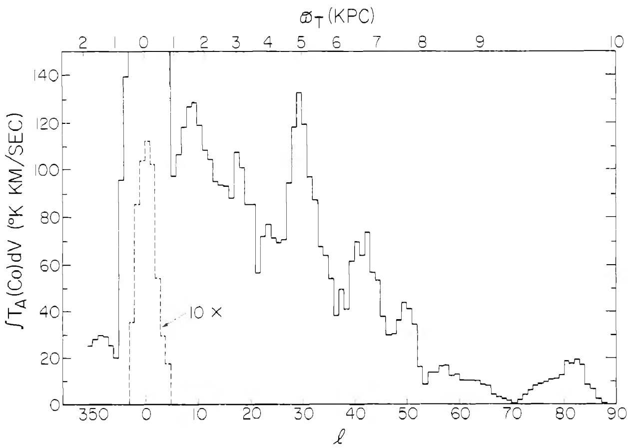

FIG. 2.—The distribution of the integrated CO intensity $\int T_A dv$ in kelvins km s^{-1} is shown as a function of longitude. The tangential radius on each line of sight is also given on the top.

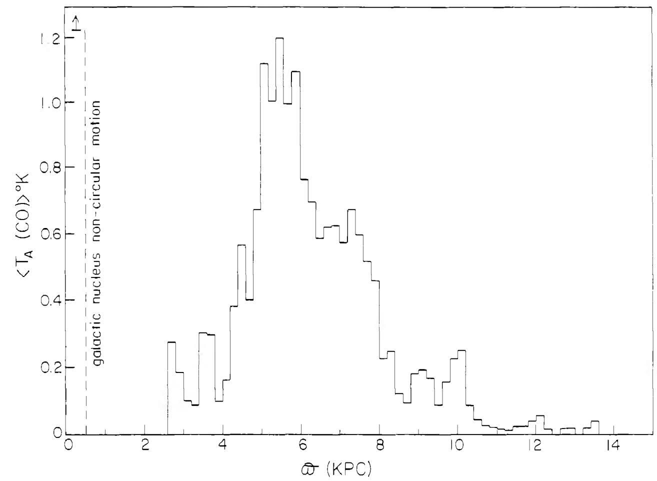

FIG. 3.—The mean CO antenna temperature as a function of radius in the Galaxy ϖ was calculated using the Schmidt (1965) rotation law to transform l, v in Fig. 2 to ϖ. We use only data at $l \geq 10°$ in order to exclude the galactic center where much of the gas clearly is not in pure rotation. Note the sharp peak in CO at radius of 5.5 kpc and dramatic falloff toward the Sun and beyond.

Essentially all the emission at $|l| \leq 4°$ is from the nucleus; both the intensities and radial velocities are high in this region. The remainder of the CO at $l > 4°$ may be shown to be inside (or outside) the solar circle where the radial velocities are positive (or negative) assuming only that angular velocity increases toward the center. Major characteristics in the distribution of molecular clouds apparent from the data in Figures 1 and 2 are: (1) *the extremely strong emission originating from the galactic nucleus at* $|l| \leq 4°$; (2) *a maximum at* $l = 30°$; *and* (3) *a sharp drop in integrated intensity beyond* $l > 45°$. The falloff of integrated intensity with increasing longitude points to an inverse relationship between molecular emission and distance from the galactic center.

a) Galactic Nucleus

The most spectacular emission is found at longitudes less than 4° corresponding to galactic radii $\tilde{\omega} < 0.8$ kpc. The very high velocities were emphasized in the first H I observations of the galactic nucleus (Rougoor and Oort 1960); the kinematics of molecules in the nucleus are a complex mixture of both radial and orbital motions with the radial motions occurring at smaller galactic radii ($\tilde{\omega} \approx 300$ pc) than was evidenced by the 21-cm observations (see Scoville *et al.* 1974 for more discussion). Special also is the extremely high abundance of molecular gas— many times the atomic hydrogen there. We have estimated in the previous CO survey that the mass of H_2 is $5 \times 10^7 M_\odot$ as compared with $4 \times 10^6 M_\odot$ in H I (Rougoor 1964).

b) Galactic Disk

For the gas outside the galactic center where circular motion is a good approximation, we use a galactic rotation curve (Schmidt 1965) to derive the galactic radius which corresponds to each observed l, v point in Figure 1 and calculate the mean CO intensity as a function of $\tilde{\omega}$ (Fig. 3). Moving out in the galactic plane *the emission rises sharply to a maximum at 5.5 kpc; beyond this peak a dramatic fall off is seen; and exterior to the Sun there are few features.*

The distribution is probably real and cannot be explained by observational bias given by the threshold for detection in the present survey ($3\sigma = 1.5$ K). Low intensity emission, uniform in some region of the Galaxy but always less than our detection limit, could significantly alter Figure 3; however, selected observations with 5 times the present sensitivity indicate that this problem is not serious (Scoville and Solomon 1975). Observations at 21 cm suggest that more serious errors occur because the galactic plane is bent and its scale height increases at large distances. The little mapping we have done in galactic latitude shows no *systematic* increase in negative velocity emission above or below the galactic plane at $l = 20°$, 30° 41°, and 44°. Moreover, where the exterior gas would have been much closer in the longitudes greater than 50°, no strong emission was seen.

A scarcity of molecules between 1 and 4 kpc is implied by both Figure 2 and Figure 3. In circular orbit this gas would appear at high velocities ($80 < V < 250$ km s^{-1}) in the longitude range 5°–25°. Its absence in Figure 3 may be caused by noncircular motions which make the transformation employed there, based on the Schmidt rotation law, inapplicable. Nevertheless, provided the emission is not fortuitously blocked by a foreground cloud at the same radial velocity, any significant features would show up in Figure 2 as an increase of $\int T_A dv$ regardless of the gas kinematics. Since the peak at $l = 8°$ is no higher than that at $l = 30°$ (corresponding to $\tilde{\omega}_T = 5$ kpc), we conclude there is no evidence of additional emission when the line of sight passes closer to the center than the tangential point at $\tilde{\omega} = 5$ kpc (excepting $l < 5°$).

III. COMPARISON WITH H I, H II, AND γ-RAYS

The galactic plane 21-cm emission (Kerr 1969; Mezger *et al.* 1970) is more pervasive in both space and velocity than the CO: there is little tendency to concentrate at $l < 40°$ and fairly strong emission is found at negative velocities ($\tilde{\omega} > R_0$). The 21-cm lines are much broader, $\Delta V \approx 30$ km s^{-1}, and most local maxima show little correspondence with those of CO (the arrows in Fig. 4 indicate the 21-cm maxima). The spectra at $l = 20°$ and 34° thus show four and seven separate CO peaks in a velocity range showing only one H I maximum. If spiral features can perhaps be traced in H I, the CO peaks might be interpreted as small condensations within the arms.

Outside the galactic nucleus there is close correspondence between the surface density of H II regions (Westerhout 1958; Mezger 1970), γ-ray emission (Stecker *et al.* 1975; Puget 1975), and the CO emission (Fig. 5). All show a peak at 5.5 kpc and decrease a factor of 6 going to 10 kpc, with striking similarity in the detailed dependence. This correlation is what is expected since dense H II regions result from formation of massive stars inside molecular clouds. Virtually every dense H II region is embedded in or on the edge of a molecular cloud, but there are many molecular clouds without dense H II regions. We guess that the lack of correlation between CO emission and observed H II regions in the galactic nucleus (Fig. 5) is caused by dust extinction of ultraviolet photons or by high optical depth of the free-free emission. Since the γ-rays are produced by cosmic-ray interactions with the interstellar gas, the similarity of the γ-ray to the CO distribution is expected if H_2 gas is the most abundant form of hydrogen in the interior of the Galaxy (Stecker *et al.* 1975).

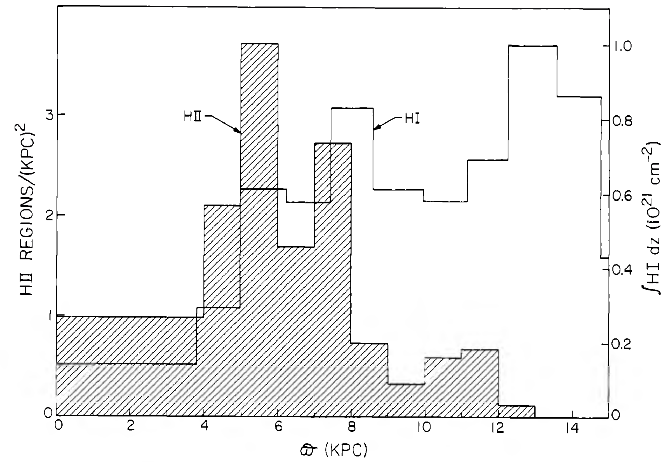

FIG. 5.—The surface density in giant H II regions (*shaded area*, Mezger 1970) and free-free continuum radiation (see Fig. 16 in Westerhout 1958) show a remarkable similarity to the radial distribution of CO (Fig. 4). In contrast the H I surface density varies little with galactic radius (Van Woerden 1965). The giant H II regions are defined to be intrinsically as luminous as Orion A = M42.

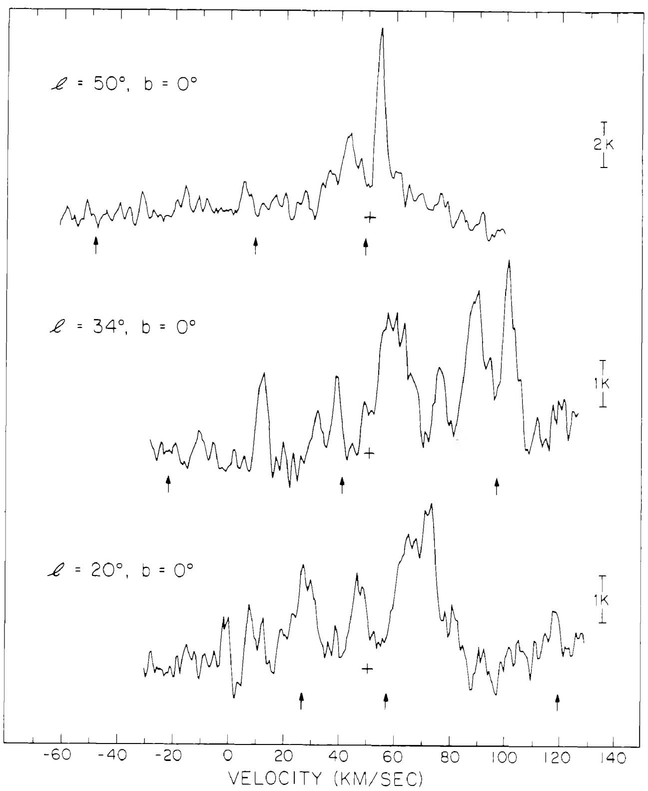

FIG. 4.—CO spectra are shown for three typical positions crossing the inner region of the Galaxy. At each position many distinct features are seen. The velocities of local maxima in 21-cm spectra at the same position are indicated by arrows (Kerr 1969). The widths of the 21-cm are typically at least 30 km s^{-1}. The intensity units are kelvins, T_A corrected for atmospheric attenuation but not for telescope beam efficiency ($\eta_B = 0.6$).

IV. H_2 DENSITY AND TEMPERATURE IN THE GALAXY

A typical line of sight crossing the inner part of the Galaxy ($10° < l < 45°$; see Fig. 4) shows five well-defined features with mean width 8 km s^{-1} and $\bar{T}_A = 2$ K (i.e., $\int T_A dv = 80$ K km s^{-1}). At $l > 50°$ there is typically one feature with $\int T_A dv \approx 16$ K km s^{-1}. The antenna temperature corrected for antenna efficiency ($\eta_B = 0.6$) and atmospheric attenuation is approximately 3.3 K, equivalent to a true Planck brightness temperature of 6.6 K. This is similar to CO intensities in nearby dark clouds; it is a factor of 10 weaker than the emission from the vicinity of strong infrared sources and compact H II regions such as W3, W51, NGC 6334, and the Kleinmann-Low nebula. If the CO levels are nearly thermalized, then the average gas kinetic temperatures are only 7 K. The relevant path length along the line of sight where these features are found is typically 10 kpc, mostly in the vicinity of the broad 5.5-kpc peak. The line-of-sight distance l between clouds is therefore 2 kpc at $4 < \tilde{\omega} < 7$ kpc as contrasted to $l \approx 10$ kpc in the solar neighborhood since less than one feature occurs in each spectrum at longitudes greater than 70°. Thus the spatial density of clouds is approximately five times as great at 5 kpc as at 10 kpc, a result reflected also in $\langle T_A \rangle$ (Fig. 3).

In estimating the mass of H_2 contained in dense clouds it is imperative that data on the ^{13}CO emission be available since the more abundant CO lines are always heavily saturated. We have recently observed the ^{13}CO emission at the positions in Figure 4 (Scoville and Solomon 1975). All features in the CO spectra are also seen in ^{13}CO, with $^{13}CO/CO$ peak intensity ratios in the range $\frac{1}{5}$ to $\frac{1}{2}$. For the analysis below $\frac{1}{3}$ is adopted as a typical intensity ratio. The density $n(H_2)$ within the clouds, consistent with this ratio, may be obtained from CO excitation and line formation theories which take account of excitation by trapped line photons (Goldreich and Kwan 1974; Scoville and Solomon 1974). In the notation of Scoville and Solomon we find that

$$n(H_2) = \gamma \left(\frac{E}{\epsilon} \frac{\Delta v}{r}\right)^{1/2} \tag{1}$$

where $\gamma \equiv [4\pi/(3\lambda^3\langle\sigma v\rangle)]^{1/2}$ is approximately constant for the transition $\sim 4 \times 10^6$ for CO, and ϵ is the CO/H_2 abundance ratio. The degree of excitation parameterized by E is equal to 50 for thermalized CO and ^{13}CO at one-third the intensity (for $[^{13}C/C] = 1/40$). Setting $\Delta v/r = 1$ km s^{-1} pc^{-1} and $\epsilon = 6 \times 10^{-5}$ (10% of all C in CO), we obtain $n(H_2) = 670$ cm^{-3} as a best estimate. A firm lower limit $n(H_2) > 150$ cm^{-3} is obtained from the ^{13}CO observations assuming that each collisional excitation of ^{13}CO results in an escaping photon and that one-half of all available ^{13}C is in ^{13}CO. If these clouds have a radius similar to nearby dark nebula $r \approx 10$ pc, the fraction of space filled by clouds being $4r/3l$ is ~ 0.7 percent at $\tilde{\omega} = 5$ kpc. Combining these numbers gives a "smoothed out" molecular hydrogen density of $\langle n(H_2)\rangle \approx 1$–$5$ cm^{-3} at 4–7 kpc. Based upon the few scans we have made at differing latitudes, we judge the full thickness between half-intensities as about 130 pc.

V. COMMENTS

We conclude that in contrast to atomic hydrogen the molecular hydrogen shows a strong density gradient with galactic radius. Much of the interstellar medium in the interior of the Galaxy $\tilde{\omega} \leq 7$ kpc is molecular: a maximum at $\tilde{\omega} \leq 400$ pc and a secondary peak at $\tilde{\omega} = 5.5$ kpc. The region between 0.5 and 4 kpc is a density minimum in both molecular and atomic gas. Whether the outer maximum is ring-shaped (i.e., fully axisymmetric) we cannot yet determine.

It seems clear that the maximum is not merely the result of a single spiral arm being coincidentally tangential to our line of sight at $\tilde{\omega} = 5.5$ kpc. Figures 2 and 3 indicate that the width of the peak is at least 2 kpc at half-intensity points, which is much greater than the thickness of spiral arms.

At $4 < \tilde{\omega} < 7$ kpc, a typical molecular cloud has a density (H_2) of ~ 700, and a temperature near 7 K. If its mass of 9×10^4 $M_\odot$ were smoothed out over its neighboring volume, the resulting hydrogen atom density would be about 5 cm^{-3} between 4 and 7 kpc and 10 cm^{-3} at the 5.5-kpc peak. Independent evidence for such high abundance of molecular hydrogen in this region is found in analysis of the γ-ray observations (Stecker *et al.* 1975).

We think it reasonable that the observed clouds should end up forming primarily into OB associations rather than bound clusters or T Tauri associations. Their internal velocity dispersion (8 km s^{-1}) is similar to that observed for stars in OB associations but much greater than the dispersion within T Tauri associations (only 1–2 km s^{-1}, Herbig 1962). Using the above densities and distribution, we find the total mass in molecular clouds to be about 1–3×10^9 $M_\odot$, mostly concentrated inside $\tilde{\omega} = 8$ kpc. If the lifetime of a cloud is 3×10^6 yr $[=(G\rho)^{-1/2}$ with $n(H_2) = 500$ cm$^3]$, then star formation would have to take place with an efficiency of 1 percent to give a current rate of star formation in the galaxy of 3 $M_\odot$ yr^{-1}.

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